Expansion of Countermine Lidar UAV-based System (CLUBS)

Joong Yong Park
Optech Inc.
7225 Stennis Airport Drive, Suite 300
Kiln, Mississippi 39556
phone: (228) 252-1004 fax: (228) 252-1007 email: joongyong.park@optech.com

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http://www.optech.com

LONG-TERM GOALS

The long-term goal of this work is to examine the utility of commercial bathymetric lidar technology solely, and in combination with commercial passive imaging spectrometers, for measuring environmental information for military applications in the littoral zone. These findings will indicate how commercial systems might evolve to achieve improved performance for rapid environmental assessment, and for deployment in unmanned aerial vehicles.

OBJECTIVES

1. A prediction of the measurement accuracy of existing bathymetric lidar systems under a wide range of environmental conditions.

2. A recommendation of design parameters leading to a smaller, light-weight airborne bathymetric lidar capable of producing data similar to that produced by the Compact Hydrographic and Rapid Total Survey (CHARTS) or the Coastal Zone Mapping and Imaging Lidar (CZMIL).

APPROACH

The existing lidar waveform simulator was created based on algebraic approximation of lidar pulse interaction with water medium. It was possible to perform system parameters optimization (altitude, angle, pulse duration, beam divergence, receiver FOV, electronic system response), predict maximal operation depth, and estimate basic environmental parameters from lidar waveform (bottom depth and reflectance, the diffuse attenuation coefficient). However, the effects of light scattering in the seawater was not properly simulated. Thus, it estimated several incorrect results such as the lidar spatial resolution at a significant depth, correction of the depth estimate for the beam stretch due to scattering.

In order to improve aforementioned issues, we developed a new lidar waveform simulator. It is based on multiple-forward and single-backward scattering concept. The lidar pulse interacts with medium experiencing scattering and dispersion. At the same time the return of the interaction is modeled by the dispersion of the fictitious viewing pulse via the optical reciprocity theorem. Using the small angle scattering approximation, the governing equation of lidar return as a function of time is eventually formulated by the multiplication of 2 irradiance distributions; one by the laser pulse and the other by

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the fictitious viewing beam. Thus, the solution of the governing equation becomes the solution of radiance distribution to form irradiance distribution. The solution of radiance is obtained via the solution of stationary radiative transfer. The radiance solution based on small angle approximation is given in the form of Fourier transform. Using the solution of laser pulse source radiance distribution it is possible to calculate irradiances and the lidar waveform with proper handling of scattering effect.

We identified several test sites to accomplish our primary objective and defined the environmental characteristics. We chose the regions of interest based on the availability of Optech's SHOALS data and sufficient ground truth. The chosen sites accounted for a wide spectrum of environmental characteristics.

We also developed a similarity measuring tool to examine how realistically the Waveform Simulator can simulate a lidar waveform. In the preliminary phase, we primarily focused on validating the influence of water properties on the simulated SHOALS waveforms. Therefore, we determined regions of interest where the actual SHOALS bottom returns have reached or nearly reached extinction.
In the later phase, we included the bottom return in the simulated waveforms for our analyses and subsequently performed the similarity tests.

To produce a conceptual design for a miniaturized, fusion-based coastal and benthic mapping system, we had several meetings to design conceptual system requirements to adopt a data fusion approach using a simple, low spatial density lidar with a high spatial resolution imaging spectrometer, and spectral processing software developed in the CZMIL program, to function as an active-passive bathymeter.

Performance of bathymetric lidar systems declines rapidly as laser power and aperture decrease. Therefore, we immediately understand the requirement for a careful analysis of the trade space. To support this analysis, market research was done to locate system components that are compatible with the InSitu Integrator UAV.

WORK COMPLETED

We simulated datasets for a wide array of surface and water column properties. Then, we ran the "depth-extraction" algorithm on the simulated waveforms. We also presented preliminary results and discussed the biases as a result of varying various environmental parameters.

In the time of conceptual design , we did the review and had contacts with different potential vendors of laser.

The main requirements (criterious) for the laser were:

- Wavelength - 532 nm
- Pulse durarion – 1-2.2 ns
- Pulse repetition rate – near 2 kHz
- Air cooling
- Best efficiency (minimum electrical power consumption)
- Minimum size

RESULTS

1. ***Range accuracy assessment of in-water optical path length measured by CZMIL and CHARTS systems***

The surface and backscatter parts of the simulated waveforms correlation well with the actual SHOALS waveforms extracted from the chosen ROIs. However, the similarity analyses on simulated waveforms revealed that the shape of the bottom return did not correlation well with the bottom return of actual waveforms.

We believe this due to the fact that the values of effective b_f used in the current version of waveform simulator are based on "small angle scattering" approximation. Subsequently, we developed a more sophisticated model and that included the effect of Volume Scattering Function (VSF). The new model would replace the current dispersion model which is based on effective b_f. The introduction of VSF would incorporate a more accurate effect of forward multiple scattering in the lidar waveform.

Oblique sounding of the delta-pulse results in several interesting properties of the lidar waveform. It was possible to simulate those characteristics using the new simulator. Several important properties are as follows.

(1) Surface reflection of the laser pulse is perfect Gaussian in case of ideal water surface. The volume backscattering starts sending scattered radiance as the laser pulse enters the water body. The edge of the pulse starts interacting with water first and followed by the rest of the pulse area. Thus, the shape of the near-surface volume backscattering signal is close to the shape of the error function which is the definite integral of the 2-D Gaussian curve from one end to the other end. The simulator shows the asymmetric near-surface volume backscattering curve; the seconfd half of the error function shows somewhat smaller rate of increase compared to the first half of the rising error function. This is because the refracted distance after the surface is different as the refracted pulse propagates and the the optical path length due to the absorption is significantly bigger in the second half. Thus, the asymmetrical shape is clearly revealed. The implication of this asymmetry is that the potential decomposition of near surface waveform into surface peak and volume backscattering will be incorrect if symmetric volume backscattering shape is assumed.

(2) The apparent bottom peak shifts to earlier time so that the bottom depth appears to be slightly shallower. This effect occurs because the relatively rapid beam dispersion near the bottom. The main cause of this phenomenon is the scattering. The scattering effect is more prominent as the water depth increases contrary to the shallow water where the absotption plays more important role. The increasing scattering optical pathlength results in the decrease of return signal. Thus, the symmetric Gaussian bottom response peak appears to be shifted to the earlier time and its symmetry is not maintained. This means that even a well-defined strong bottom peak with a good separation from the volume backscattering background has certain depth bias. The degree of shift is strongly related to the scattering coefficient.

(3) We might say the irradiance distribution on the z-plane perpendicular to the propagation of the laser pulse is close to Gaussian in general. Due to the oblique sounding, each points on the z-plane has different optical path length. When the Gaussian irradiance distribution is multiplied by the varying optical path length, the peak of the irradiance distribution undergoes a shift of

maximum point on the z-plane. However, this effect does not significantly affect the observed waveform because the waveform is the result of integral of the irradiance distribution on the z-plane.

The depth accuracy assessment using simulated lidar waveforms generated from the advanced lidar waveform simulator shows acceptable depth error in the IHO standard 1A. The important point studied during the depth accuracy assement is that the use of conventional "half-peak to half-peak" algorithm to calculate slant distance results in significantly high depth error compared to the counterpart "peak to peak" algorithm. The assumption of the half-peak to half-peak algorithm is that the peak width of the surface Fresnel peak and the bottom peak is not significantly different. In relatively clear water with shallow depth, this is a very good assumption because the minimal beam stretching does not cause significant increase in the effective beam radius. However, in majority of coastal bathymetric lidar waveform the scattering is a real issue. The scattering causes the beam stretching and the stretched beam makes much wider bottom peak compared to the width of the surface peak in the lidar waveform.

After the atmosphere-surface correction the blue channel profile along the scanline still shows significant asymmetry even in the deep water. This phenomenon necessiates the application of the scanline asymmetry correction. Normally this effects is visible from UV up to blue VIS channels. However, some CASI systems requires the correction up to green channels. Since it is the property of the CASI system, the new solution is to have a parameter that sets the upper wavelength limit.

Scanline asymmetry correction evaluates the curvy profile using the polynomial regression and the correction is performed in a manner that the curve is supressed to flat line. Thus, the key to the successful correction is the accurate modeling of the curve using proper polynomial regression. The scanline data on which the regression is performed comes from the optically deep water. Sometimes the assumption is not satisfied. In that case the curve will be very unrealistic shape due to shallow bottom reflectance effect or asymmetric strong sun glint background etc. Thus, it is very important to set a tolerance on the regression coefficients.

The previous version of the data processing software has the overlapping pixel handling methods in the mosaic. The simple available options were selecting darker or brighter pixels. For the most of coastal ocean image, the darker pixel option performs well because brigher pixel is likely to be the result of unwanted radiance from atmosphere or the floating algae. However, that approach is not very well suited for the land scene especially artifical objects. Thus, a new option was added and the concept is that the distortion of the land or artificial objects will be minimized when the concept of minimal nadir angle was utilized. To achieve this goal it is required to calculate the viewing zenith angle for all pixels. The calculation of viewing zenith angle requires roll, pitch, and heading of the platform.

2.4 Deep water seed image selection

Spectral optimization estimates large number of parameters for all pixels. Thus, it is always a good idea to utilize when any parameters are known. The idea of seed image is that the deep water image normally is free from the influence of bottom. Thus, it is possible to calculate the water constituent parameters with better accuracy. And then, this water parameters can be used as a seed parameters for all image because water quality does not have drastic spatial variation. Previous version of the software utilized automatic selection of the seed region in the optically deep part of the image. However, it is often difficult or inaccurate. Thus, new scheme recommends user to select the optically deep region and it provides the tools to create a seed image.

2. *Conceptual Design for a miniaturized, fusion-based coastal and benthic mapping system*

From researches based on the system requirements for small UAS bathymetric lidar system were provided from NAVO, the conceptual system parameters were decided for further research (Table 1).

Table 1. System parameter for the conceptual design

System Parameter	Target
Max Optical Depth	2.0 KDmax
Min Depth(meters)	1
IHO Order	1a
Horizontal Position Accuracy	5meters+5% of depth
Vertical Accuracy	a=0.5, b=0.013
Feature Detection	Cubic >2meters
Operational Altitude	>750m
Aircraft Operational Speed	60 kts
Swath Width	>60% of altitude
Laser Spot Spacing	3m
Laser Operation	Hydro/Topo 2kHz
Data Processing ratio	Processing 1.0: collection 1:0
Camera Capability	Time&Position tagged digital color video
Sensor Weight	37.5 lbs

In this phase of the project a preliminary design for the scanner was completed. The specification of the project motivate that the scanner should be small in size, weight and power consumption. The main constraints encountered are 1) a diffraction/refraction system cannot be use as those are wavelength dependent and it is the intent to create a unified lidar and spectral system, 2) only mirror systems can be used for a unified system and 3) based on previous research, the incidence angle of the laser beam on the water surface has to be about 20°.

These constraints for the space, size and power as well as the intention of a unified system motivate 1 mirror 2 axis scanner design. The basic structure is shown in Figure 1.

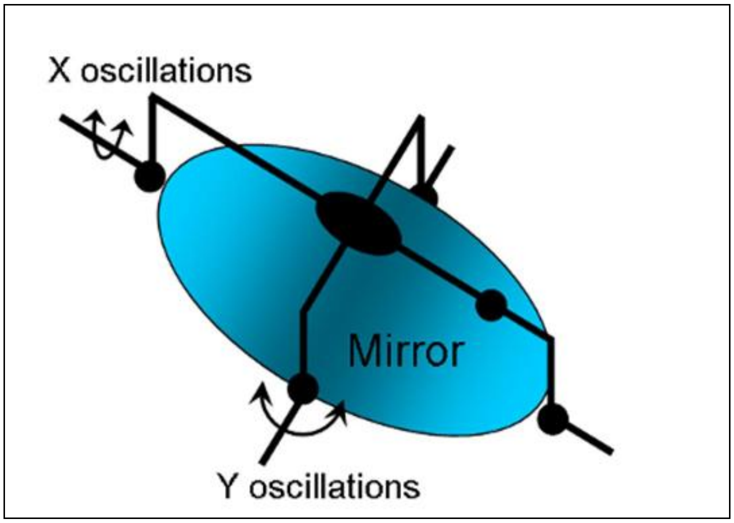

Figure 1: One-mirror 2-axis design

The InSitu Integrator UAV comes standard with the Rockwell Collins Athena 611 Flight Control System. One option is to use only the existing Athena 611 system. Another option is to use a second IMU in conjunction with the Athena 611 system. The total weight of the Athena 611 system is approximately 9.7 lbs including the cables and IMU. An additional IMU would need to be light-weight, while still meeting the horizontal positional accuracy specifications of 2 meters. Several microelectromechanical system (MEMS) IMUs have been researched for this role. While these systems are very compact and light-weight, all failed to meet the accuracy requirements. We are still searching for an IMU that could be appropriately used with the existing system.

Our review (we invited Dr. Eugene Shklovsky from Optech, Toronto to participate in this project) demonstrated that the best laser for our case is a laser from Bright Solution. The discription below is based on BS official proposal to Optech.

The present document is a preliminary proposal of a customized short pulse Diode-Pumped Solid State (DPSS) laser source for lightweight and compact LIDAR instruments operating at 532 nm. The device is based on a compact oscillator with a Nd 3+ crystal host as an active medium; the oscillator provides the amount of energy (2 to 2.5 mJ) required for an extra-cavity SHG process.

Main building blocks are mounted and heat-dissipated on an aluminum air cooled structure: the laser resonator is pumped by 2 kHz pulsed fiber coupled diode lasers; the 1064 nm laser output is converted to 532 nm through an extra-cavity Second Harmonic Generation module; output beam conditioning optics will shape the output beam to the desired size and divergence.
All the critical optical modules are actively temperature stabilized through internal high precision TEC controllers. The body of the main heatsink is cooled through forced air by external thermo-static fans. The driving electronics are tightly integrated in a compact monolithic platform.

The laser Resonator is a miniaturized optical cavity emitting 1 ns long pulse thanks to Bright Solutions proprietary fast q-switching technology, with output energy of at least 3.1 mJ at 1064 nm, linearly polarized for optimized second harmonic generation. Extra-cavity SHG is preferred for short pulse generation.

The gain module assembly consists of a customized Nd:3+ doped laser crystal assembly derived by our standard WedgeHB models; the laser cavity optics design is intended to produce an infrared output beam with a high-enough beam quality/ homogeneity to allow an efficient second harmonic generation process (comparable systems in BS range of products achieve SHG efficiencies in the range of 50-65%). The resonator works in giant pulse Q-switching regime which is obtained through the use of a Pockels cell (Bright Solutions design both for cell and driver electronics, derived from devices employed in all of our standard products).

According to our standard production methods, all of the cavity optics are permanently aligned and insensitive to vibration/shock as found even in a harsh aerospace environment.

The resonator unit is sealed in dry air, sea-level pressure to avoid external contaminants. It can normally withstand pressure variations in the range 0 atm/+2 atm.

The internal operating temperature is defined and precisely controlled by the TEC coolers.

The recommended storage temperature is 0°C-50°C but can be extended on request to -20°C/+80°C.

A set of Beam Conditioning optics provides optimization of the green output beam in terms of spot size/divergence. The SHG Module too is permanently aligned (shock/vibration proof) and sealed in dry air.

The Pump Diode Modules are high power fiber-coupled diode laser devices produced by Bright Solutions (BDL-90); they provide up to 90 W peak power through the end of a multimode fiber optic, making them easily replaceable in the event of a failure. Thermal control of the Pumping Modules is effected via a ruggedized TEC temperature controller. In terms of power consumption, the TEC control usually benefits of a relatively high internal temperature set point (30 to 40°C). Power consumption relevant to temperature control will be optimized when ambient temperature ranges from 15 to 35 °C; it will increase for very high (35° to 40°C) and very low (0°C to 15°C) temperature, due to higher amount of electrical power for heating and cooling the interested optical parts.

The tightly integrated electronic platform will be miniaturized in order to fit in the same footprint as the compact laser head. It will feature 28V power supply input for direct use in airborne application.-

Bright Solutions is experienced in the design and manufacturing of customized and standard high power DPSS lasers for industrial and aerospace applications.

The basic laser design of the present proposal will include several laser power modules designed by Bright Solutions and regularly manufactured to be used in several standard Wedge DPSS laser models. In particular laser diode pumps, high power laser gain modules and SHG stages will benefit of established standard manufacturing processes, availability of reliability data, skilled and trained personnel. Nevertheless remarkable customization effort will be primarily dedicated to:

- higher pulse energy;
- extreme pointing stability performance;
- extended temperature range of operation;
- extreme miniaturization and integration of optical and electronic modules.

Figure 2 demonstrates one of Bright Solution lasers that is close to the parameters of the proposed laser.

Figure 2. One of Bright Solution lasers similar to the proposed laser.

IMPACT/APPLICATIONS

This project has the potential to impact the operational Navy in two significant ways. First, the study is important to NAVO in their worldwide deployment of CZMIL, and second, it is of interest to agencies interested in deploying bathymetric lidar on smaller platforms. Both require expert knowledge as to how bathymetric lidar performance varies with electro-optical design, physical deployment, water column conditions, and seafloor characteristics, and how data processing algorithms function to produce the required bathymetric measurements.

RELATED PROJECTS

Coastal Zone Mapping and Imaging Lidar (CZMIL). CZMIL is a strategic partnership between Optech, Inc. and the Department of Marine Science at the University of Southern Mississippi. This effort is leading to improve performance in shallow water and achieve water column and seafloor characterizations. The CZMIL project will also establish an industry/government/academic center of expertise for bathymetric lidar.